

# HIGH DATA RATE ETHERNET TRANSPORT FACILITY OVER DIGITAL SUBSCRIBER LINES

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## FIELD OF THE INVENTION

The present invention relates generally to telecommunication systems and more particularly relates to a system for transporting Ethernet over digital subscriber lines.

## BACKGROUND OF THE INVENTION

15 *THIS* There is a growing need among both individuals and enterprises for access to a commonly available, cost effective network that provides speedy, reliable services. There is high demand for a high-speed data network, one with enough bandwidth to enable complex two-way communications. Such an application is possible today if, for example, access is available to a university or a corporation with sufficient finances to build this type of network.

20 But for the average home computer user or small business, access to high speed data networks is expensive or simply impossible. Telephone companies are therefore eager to deliver broadband services to meet this current explosion in demand.

*THIS ALSO* One of the problems is that millions of personal computers have found their place in the home market. Today, PCs can be found in approximately 43% of all United States  
25 households and a full 50% of United States teenagers own computers. Virtually every PC sold today is equipped with a modem, enabling communication with the outside world via commercial data networks and the Internet. Currently, people use their PCs to send and receive e-mail, to access online services, to participate in electronic commerce and to browse the Internet. The popularity of the Internet is such that there are an estimated 50 million users  
30 around the globe. These figures indicate that in the past few years the personal computer has fueled a dramatic increase in data communications and the corresponding demands on the data networks that carry the traffic.

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The Internet serves as a good example of the increased demands that have been placed on data networks. At first, Internet access consisted of text only data transfers. Recently, with the popularity of the World Wide Web (WWW) and the construction of numerous sites with high quality content, coupled with the development of Internet browsers such as Mosaic, Netscape Navigator and Microsoft Explorer, the use of graphics, audio, video and text has surged on the Internet. While graphics, audio and video make for a much more interesting way to view information as opposed to plain text, bandwidth consumption is significantly more. A simple background picture with accompanying text requires approximately 10 times more bandwidth. Because of the increased requirement for bandwidth, activities such as browsing home pages or downloading graphics, audio and video files can take a frustratingly long period of time. Considering that the multimedia rich World Wide Web accounts for more than one quarter of all Internet traffic, it is easy to see why the demand for bandwidth has outpaced the supply. In addition, the creative community is pushing the envelope by offering audio and full motion video on numerous sites to differentiate themselves from the millions of other sites competing for maximum user hits.

As use of the Internet and online services continues to spread, so does the use of more complex applications, such as interactive video games, telecommuting, business to business communications and videoconferencing. These complex applications place severe strains on data networks because of the intensive bandwidth required to deliver data-rich transmissions. For example, a telecommuter who requires computer aided design (CAD) software to be transported over the data network requires a high-bandwidth data pipeline because of the significant size of CAD files. Similarly, a business to business transaction in which large database files containing thousand of customer records are exchanged also consumes large amounts of bandwidth. The same is true for users seeking entertainment value from sites offering high quality video and audio. The lack of available bandwidth in today's data networks is the primary barrier preventing many applications from entering mainstream use. Just as processing power limited the effectiveness of early PCs, bandwidth constraints currently limit the capabilities of today's modem user.

Most computer modem users access data through the standard telephone network, known as plain old telephone service (POTS). Equipped with today's speediest modems, dial up modems on a POTS network can access data at a rate of 28.8, 33.6 or 56 Kbps. Dial up modem transmission rates have increased significantly over the last few years, but POTS

throughput is ultimately limited to 64 Kbps. While this rate may be acceptable for some limited applications like e-mail, it is a serious bottleneck for more complex transactions, such as telecommuting, videoconferencing or full-motion video viewing. To illustrate, full motion video compressed, using the Motion Picture Entertainment Group (MPEG)-2 standard requires a data stream of approximately 6 Mbps, or roughly 208 times the throughput of a 28.8 Kbps modem. Thus, using today's dial up modems, it would take more than 17 days to capture two hours of video. As bandwidth demands continue to grow, providers search for better ways to offer high speed data access. Further complicating the problem is the need to deliver all these complex services at an affordable price.

10 *Jul 1997* Today's most popular data access method is POTS. But as discussed previously, POTS is limited when it comes to large data transfers. An alternative to POTS currently available is Integrated Services Digital Network (ISDN). In the past few years, ISDN has gained momentum as a high-speed option to POTS. ISDN expands data throughput to 64 or 128 Kbps, both from the network to the home and from the home back to the network, and can be technically made available throughout much of the United States and in many other parts of the globe. Similar to POTS, ISDN is a dedicated service, meaning that the user has sole access to the line preventing other ISDN users from sharing the same bandwidth. ISDN is considered an affordable alternative, and in general, ISDN is a much better solution for applications such as Web browsing and basic telecommuting. However, like POTS, it severely limits applications such as telecommuting with CAD files and full-motion video viewing. The latter requires roughly 39 times the throughput than that provided by ISDN. Multichannel multipoint distribution service (MMDS), a terrestrial microwave wireless delivery system, and direct broadcast satellite (DBS), such as DirecTv and US Satellite Broadcasting (USSB), are wireless networks. They both deliver high bandwidth data streams to the home, referred to as downstream data, but neither has a return channel through which data is sent back over the network, referred to as upstream data. Although it is a relatively affordable system to deploy for broadcast applications, because it requires no cable wires to be laid, it falls short in interactive access. In order to use a wireless system for something as basic as e-mail, an alternate technology such as a telephone line must be used for the upstream communications.

Another network delivery system is asymmetric digital subscriber line (ADSL). Offering a downstream capacity of 6 Mbps or more to the home, ADSL has the downstream capacity to handle the most complex data transfers, such as full motion video, as well as an

upstream capacity of at least 500 Kbps. However, due to its limitation of downstream bandwidth capacity, it essentially is a single service platform. Also, since it has to overcome the challenge of reusing several thousand feet of twisted pair wiring, the electronics required at each end of the cable are complex, and therefore currently very expensive.

5 JLS 107 Hybrid fiber coax (HFC), a network solution offered by telephone and cable companies, is yet another option for delivering high bandwidth to consumers known in the art. However, HFC has limitations. HFC networks provide a downstream capacity of approximately 30 Mbps, which can be shared by up to 500 users. Upstream bandwidth is approximately 5 Mbps and also is shared. A disadvantage with HFC is that shared bandwidth and limited upstream capacity become serious bottlenecks when hundreds of users are sending and receiving data on the network, with service increasingly impaired as each user tries to access the network.

It is a current trend among telephone companies around the world to include existing twisted pair copper loops in their next generation broadband access networks. Hybrid Fiber Coax (HFC), a shared access medium well suited to analog and digital broadcast, comes up short when utilized to carry voice telephony, interactive video and high speed data communications at the same time.

Fiber to the home (FTTH) is still prohibitively expensive in the marketplace that is soon to be driven by competition rather than costs. An alternative is a combination of fiber cables feeding neighborhood Optical Network Units (ONUs) and last leg premises connections by existing or new copper. This topology, which can be called fiber to the neighborhood (FTTN), encompasses fiber to the curb (FTTC) with short drops and fiber to the basement (FTTB), serving tall buildings with vertical drops.

One of the enabling technologies for FTTN is very high rate digital subscriber line (VDSL). VDSL is an emerging standard that is currently undergoing discussion in ANSI and ETSI committees. The system transmits high speed data over short reaches of twisted pair copper telephone lines, with a range of speeds depending upon actual line length.

## SUMMARY OF THE INVENTION

The present invention is a facility transport system for transporting Ethernet over digital subscriber lines. The system is referred to as 100BaseS and is capable of transmitting 100 Mbps Ethernet over existing copper infrastructure up to distances of approximately 400 meters. The system of the present invention can achieve payload bit rates from 25 to 100 Mbps in increments of 25 Mbps. A bit rate of 25 Mbps is achieved using only a single copper wire pair. Each increment of 25 Mbps utilizes an additional copper pair. Note that each pair used provides a bidirectional 25 Mbps link, i.e., downstream and upstream. Thus, four copper wire pair connections provide 4 x 25 Mbps downstream channels and 4 x 25 Mbps upstream channels.

The system utilizes framing circuitry to adapt the 100BaseT input data signal to up to four separate output signals. A DSL Ethernet Port card couples the modem to each twisted pair used. Each DSL Ethernet Port card comprises modem transmitter and receiver circuitry for sending and receiving 100BaseS signals onto its respective twisted pair wires.

The system utilizes quadrature amplitude modulation (QAM). QAM is the most commonly used form of high-speed modulation over voice telephone lines. The system also utilizes frequency division multiplexing (FDM) to separate downstream channels from upstream channels. In addition, FDM is also used to separate both the downstream and the upstream channels from POTS and ISDN signals. A substantial distance in frequency is maintained between the lowest data channel and POTS frequencies to permit the use of very simple and cost effective POTS splitters, which are actually splitters/combiners. The upstream channel is placed above the downstream channel in frequency. The downstream and upstream data channels are separated in frequency from bands used for POTS and ISDN, enabling service providers to overlay 100BaseS on existing services.

The 100BaseS system of the present invention combines copper access transmission technology of Ethernet based services with Quality of Service (QoS) guaranteed by the SRVP protocol and is capable of being fully managed through an SNMP agent. The 100BaseS transport facility can deliver symmetrical data at 28.125 Mbps (net 25 Mbps) per copper pair for a total of 112.5 Mbps (net 100 Mbps) over the unscreened, twisted pair telephone wires originally intended for bandwidths of between 300 Hz and 3.4 KHz. The invention uses QAM modulation and blind equalization to achieve a high transmission speed over existing copper infrastructure. In addition, the system is able to cope with several sources of noise

such as impulse noise, e.g., POTS transients, radio frequency interference (RFI) noise and crosstalk noise, i.e., both near end crosstalk (NEXT) and far end crosstalk (FEXT). In terms of RF emissions, the system can operate using underground cabling as well as overhead distribution cabling.

5           The 100BaseS system has applications in the small office/home office (SOHO) market and can be installed in industrial areas or business districts where most of the copper infrastructure is of shorter distances. The small office/home office market has greatly developed in recent years and is eagerly waiting for LAN extension solutions. The need for connecting between several buildings of the same company or between headquarters to  
10 branches, dictates either using a leased line such as T1/T3 which is very expensive or a POTS/ISDN modem which is very slow. The 100BaseS system of the present invention can be applied to these markets while achieving better price performance for both the Telephone Company and the end user.

          There is provided in accordance with the present invention a point to point facility  
15 transport system for the transport of 100BaseTX Ethernet frame data over N copper wire pairs connecting a central office facility to a customer premise comprising N downstream transmission paths for transporting 100BaseTX Ethernet frame data transmitted from the central office facility destined to the customer premise, N upstream transmission paths for transporting 100BaseTX Ethernet frame data transmitted from the customer premise destined  
20 to the central office facility, first modem means located at the central office facility and coupled to one end of the N downstream transmission paths and one end of the N upstream transmission paths, second modem means located at the customer premises and coupled to the other end of the N downstream transmission paths and the other end of the N upstream transmission paths, wherein the first modem means and the second modem means are  
25 operative to place onto and receive from the N copper wire pairs, data frames encapsulating the Ethernet frame data and wherein N is a positive integer in the range of one to four.

          The downstream transmission path utilizes quadrature amplitude modulation (QAM) to transport the Ethernet frame data from the central office facility to the customer premise. The upstream transmission path utilizes quadrature amplitude modulation (QAM) to transport  
30 the Ethernet frame data from the customer premise to the central office facility.

          The first modem means and the second modem means further includes a physical layer module for performing physical layer functions for 100BaseTX Ethernet, the physical layer module operative to communicate over a Media Independent Interface (MII) bus, a data

splitter adapted to divide the MII data stream into N output data streams, each output data stream destined for a transmitter, N transmitters for coupling to the N copper wire pairs, each transmitter adapted to modulate one of the data streams output of the data splitter so as to generate a transmit signal therefrom suitable for transmission onto one of the N copper wire pairs, N receivers for coupling to the N copper wire pairs, each receiver adapted to demodulate a signal received from one of the N copper wire pairs so as to generate a receive data signal therefrom, a data collector adapted to receive the N receive data signals from the N receivers and to combine and reorganize the N receive data signals into a single data stream for output via the physical layer module in a form compatible with 100BaseTX. The facility transport system further comprises an auto sense unit operative to sense the number of transmitters and receivers installed in a modem.

There is also provided in accordance with the present invention a point to point facility transport system for the transport of 100BaseTX Ethernet frame data and plain old telephone service (POTS) over N copper wire pairs connecting a central office facility to a customer premise comprising N downstream transmission paths for transporting 100BaseTX Ethernet frame data and POTS transmitted from the central office facility destined to the customer premise, N upstream transmission paths for transporting 100BaseTX Ethernet frame data and POTS transmitted from the customer premise destined to the central office facility, first modem means located at the central office facility and coupled to one end of the N downstream transmission paths and one end of the N upstream transmission paths, second modem means located at the customer premises and coupled to the other end of the N downstream transmission paths and the other end of the N upstream transmission paths, first splitter means coupled to the first modem means and to the V copper wire pairs, second splitter means coupled to the second modem means and to the N copper wire pairs, wherein the first modem means and the second modem means are operative to place onto and receive from the N copper wire pairs data packets encapsulating the 100BaseTX Ethernet frame data, wherein the first splitter means and the second splitter means are operative to combine and split the POTS and N downstream and N upstream transmission path signals, wherein N is a positive integer in the range of one to four.

There is further provided in accordance with the present invention a point to point facility transport system for the transport of 100BaseTX Ethernet frame data over N copper wire pairs connecting a central office facility to a customer premise comprising N downstream transmission paths for transporting 100BaseTX Ethernet frame data transmitted

from the central office facility destined to the customer premise, N upstream transmission paths for transporting 100BaseTX Ethernet frame data transmitted from the customer premise destined to the central office facility, switch means located at the central office facility and coupled to one end of the N downstream transmission paths and one end of the N upstream transmission paths, a network element located at the customer premises and coupled to the other end of the N downstream transmission paths and the other end of the N upstream transmission paths, wherein the switch means and the network element are operative to place onto and receive from the N copper wire pairs data frames encapsulating the 100BaseTX Ethernet frame data.

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## BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

Fig. 1 is a block diagram illustrating the 100BaseS transport facility of the present invention as applied to a sample telephony application;

Fig. 2 is a block diagram illustrating a sample customer premises network utilizing the 100BaseS transport facility of the present invention;

Fig. 3 is a block diagram illustrating an optical network unit connected to multiple customer premises via the 100BaseS transport facility;

Fig. 4 is a block diagram illustrating the 100BaseS modem of the present invention in more detail;

Fig. 5 is a diagram illustrating the channel spectrum of the 100BaseS signal of the present invention;

Fig. 6 is a block diagram illustrating the transmit portion of the 100BaseS modem of the present invention in more detail;

Figs. 7A and 7B are block diagrams illustrating the receive portion of the 100BaseS modem of the present invention in more detail; and

Fig. 8 is a diagram illustrating the far end cross talk at 500 meters for an example implementation of the 100BaseS.

## DETAILED DESCRIPTION OF THE INVENTION

### Notation Used Throughout

The following notation is used throughout this document.

Term	Definition
ADSL	Asymmetric Digital Subscriber Line
AGC	Automatic Gain Control
ANSI	American National Standards Institute
BER	Bit Error Rate
CAD	Computer Aided Design
CO	Central Office
DBS	Direct Broadcast Satellite
DSL	Digital Subscriber Loop
ETSI	European Telecommunications Standards Institute
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FEXT	Far End Crosstalk
FIFO	First In First Out
FTTB	Fiber to the Building
FTTC	Fiber to the Curb
FTTCab	Fiber to the Cabinet
FTTEx	Fiber to the Exchange
FTTH	Fiber to the Home
FTTN	Fiber to the Node
HFC	Hybrid Fiber Coax
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
LAN	Local Area Network
MII	Media Independent Interface
MMDS	Multichannel Multipoint Distribution Service
MPEG	Motion Picture Entertainment Group
NEXT	Near End Crosstalk
NIC	Network Interface Card
NT	Network Termination
NTP	Network Termination Point
ONU	Optical Network Unit
PBX	Private Branch Exchange
PC	Personal Computer
PLL	Phase Lock Loop
POTS	Plain Old Telephone Service
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RF	Radio Frequency
RFI	Radio Frequency Interference
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio

SOHO	Small Office/Home Office
TDMA	Time Division Multiple Access
USSB	US Satellite Broadcasting
UTP	Unshielded Twisted Pair
VCXO	Voltage Controlled Crystal Oscillator
VDSL	Very High Speed Digital Subscriber Line
WAN	Wide Area Network
WWW	World Wide Web

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### General Description

The present invention is a facility transport system for transporting Ethernet over digital subscriber lines. The system is referred to as 100BaseS and is capable of transmitting 100 Mbps Ethernet over existing copper infrastructure up to distances of approximately 400 meters. The system of the present invention can achieve payload bit rates from 25 to 100 Mbps in increments of 25 Mbps. A bit rate of 25 Mbps is achieved using only a single copper wire pair. Each increment of 25 Mbps utilizes an additional copper pair. Note that each pair used provides a bidirectional 25 Mbps link, i.e., downstream and upstream. Thus, four copper wire pair connections provide 4 x 25 Mbps downstream channels and 4 x 25 Mbps upstream channels.

The system utilizes quadrature amplitude modulation (QAM). QAM is the most commonly used form of high speed modulation over voice telephone lines. The system also utilizes frequency division multiplexing (FDM) to separate downstream channels from upstream channels. In addition, FDM is also used to separate both the downstream and the upstream channels from POTS or ISDN signals. A substantial distance in frequency is maintained between the lowest data channel and POTS frequencies to permit the use of very simple and cost effective POTS splitters, which are actually splitters/combiners. The upstream channel is placed above the downstream channel in frequency. The downstream and upstream data channels are separated in frequency from bands used for POTS and ISDN, enabling service providers to overlay 100BaseS on existing services.

The 100BaseS system of the present invention combines copper access transmission technology of Ethernet based services with Quality of Service (QoS) guaranteed by the SRVP protocol and is capable of being fully managed through an SNMP agent. The 100BaseS transport facility can deliver symmetrical data at 28.125 Mbps (net 25 Mbps) per copper pair for a total of 112.5 Mbps (net 100 Mbps) over the unscreened, twisted pair telephone wires originally intended for bandwidths of between 300 Hz and 3.4 KHz. The invention uses

QAM modulation and blind equalization to achieve a high transmission speed over existing copper infrastructure. In addition, the system is able to cope with several sources of noise such as impulse noise, e.g., POTS transients, radio frequency interference (RFI) noise and crosstalk noise, i.e., both near end crosstalk (NEXT) and far end crosstalk (FEXT). In terms  
5 of RF emissions, the system can operate using underground cabling as well as overhead distribution cabling.

Both the LAN, i.e., Ethernet frames, and POTS services, i.e., voice, may be transmitted over a common optical access network before final distribution over a copper distribution network. Alternatively, in the case where LAN services are provided by an  
10 overlay network, an Optical Network Unit (ONU) is co-located with an existing copper network distribution point where the LAN and POTS services are combined for transmission over the existing copper distribution network.

*JWS AG* In one installation application of the invention, 100BaseS transmission would be used on shorter exchange lines when the switch or ONU is located in a serving exchange building.  
15 The switch or ONU may be sited in different locations forming different architectures for a hybrid optical network. Some of these architectures include: fiber to the cabinet (FTTCab), fiber to the curb (FTTC), fiber to the node (FTTN), fiber to the building (FTTB) and fiber to the exchange (FTTEx).

*JWS A77* The 100BaseS transport facility of the present invention supports both LAN and  
20 POTS services sharing the same copper distribution cable. The POTS and the LAN services are separated close to the point where the combined signals enter the customer premises. This is achieved by a POTS splitter filter, i.e., splitter/combiner filter, which may or may not be part of the network termination (NT). The 100BaseS system is a point to point transmission system even though the core modem is a blind modem that is able to support  
25 point to multipoint communications. The network termination interface at the customer premises can be the widely used 100BaseT RJ-45 interface. The customer can hook up any common 100BaseT equipment, such as an Ethernet switch or hub, or any product that has an Ethernet network interface card (NIC). The network interface unit will respond to test and management messages originated by any SNMP network management system.

*JWS A87* The system supports two latency modes that can be modified by software or through  
30 the network management: with an interleaver resulting in a latency of less than 20 msec; without an interleaver resulting in a latency of less than 200 microseconds.

## 100BaseS Applications

A block diagram illustrating the 100BaseS transport facility of the present invention as applied to a sample telephony application is shown in Figure 1. The public switched telephone network (PSTN) 110 is shown with one central office (CO) switch 114 coupled to Internet service provider (ISP) 136. The ISP comprises an access switch 138 that is shown coupled to two network elements 140, 142. Another central office switch 112 is shown connected by a fiber link to the access switch 116.

The access switch 116 is shown connected to two access switches 118, 134 via 100BaseS connections. It is important to note that all 100BaseS connections actually comprise from one to four twisted pair wires, depending on the number of pairs implemented. The two access switches 118, 134 represent edge devices for two separate customer premises. The access switch 118 is shown connected to computer workstations 120, 122 and to an Ethernet hub 124. The Ethernet hub, in turn, is connected to two computer workstations 126, 128. Data communications between the access switch and the computer workstations and the Ethernet hub are carried over 100BaseT links. The access switch 134 is shown coupled to computer workstations 130, 132. Communications between the computer access switch and the computer workstations occur over 100BaseT links.

It is important to note that the network comprising computer workstations and the Ethernet hub, shown connected to the access switch in the example in Figure 1, is for illustrative purposes only. One skilled in the art can assemble numerous other configurations without departing from the spirit of the invention. The access switch of the present invention can be coupled to any device able to communicate using 100BaseT.

Each of the access switches comprises 100BaseS modems that communicate with each other using the 100BaseS modulation and protocol scheme disclosed herein. The modems, including the transmitter and receiver portions, incorporated in the access switches are described in more detail hereinbelow.

A block diagram illustrating a sample customer premises network utilizing the 100BaseS transport facility of the present invention is shown in Figure 2. This figure shows a central office 12 coupled to a private branch exchange (PBX) 14 and a LAN/WAN 16. The connection between the central office and the PBX carries voice traffic and the connection between the central office and the switch 18 within the LAN/WAN carries data traffic. Both the PBX and LAN/WAN are located on the customer premises 17.

The PBX is coupled to a plurality of POTS splitters 22 which function to combine the 100BaseS transmission signal from each copper wire pair with the POTS voice signal. The LAN/WAN is shown comprising at least a switch 18, for example, which is coupled to the POTS splitters via 100BaseS modems 20. The LAN/WAN can comprise any combination of networking equipment. The LAN/WAN is connected to the 100BaseS modem via a 100BaseT connection. Note that throughout this document, the term POTS splitter implies a device that functions to both split and combine the 100BaseS (up to four twisted wire pairs) and POTS signals.

*FIG A11* POTS splitters 22 communicate to POTS splitters 24 which are typically physically located in remote locations in different areas of the customer premises. For example, the customer premises may be a large university campus with communication links spanning out to each building within the campus. The communication links would carry a combination of 100BaseS and POTS traffic. With reference to Figure 2, the links between the POTS splitters 22 and 24 carry a combined 100BaseS transmission signal in addition to the POTS voice signal. The PBX and the network equipment would typically be installed in the telecommunications equipment room that also serves as the service entrance or network termination point (NTP) to the telco lines from the central office.

In Figure 2, each of the POTS splitters 24 are connected to telephone voice terminals 26 and 100BaseS modems 20. Any 100BaseT capable device such as computer workstations 28 can be connected to 100BaseS modems 20.

*FIG A12* A block diagram illustrating an optical network unit connected to multiple customer premises via the 100BaseS transport facility is shown in Figure 3. An example central office 150 within the PSTN 110 is shown coupled to an optical network unit (ONU) 152. The fiber is terminated on a high speed switch 154 that comprises a plurality of 100BaseT ports. 100BaseS modems 156, 158 are shown coupled via 100BaseT to the high speed switch 154. The 100BaseS modem 156 is coupled to 100BaseS modem 162 within customer premises #1 160. The 100BaseS modem 162, in turn, is connected to the premises distribution network 164. The premises distribution network represents any 100BaseT capable network. Shown coupled to the premises distribution network are computer workstations 166, 168.

Similarly, 100BaseS modem 158 is connected to 100BaseS modem 172 located in customer premises # 2 170. 100BaseS modem 172 is connected to the premises distribution network 174. Here too, the premises distribution network 174 represents any 100BaseT

capable network. Computer workstations 176, 178 are shown connected via 100BaseT to the premises distribution network.

### 100BaseS Modem and Framer

A block diagram illustrating the 100BaseS modem of the present invention in more detail is shown in Figure 4. The 100BaseS modem, generally referenced 180, comprises a PHY or physical portion and a framer portion. The modem is adapted to provide a bidirectional connection between a 100BaseT port 182 and a 100BaseS port 198. The physical layer portion in the modem comprises a 100BaseTX module 184 ('x' ranges from 1 to 4) which is adapted to receive a 100BaseT signal 182 from a 100BaseT port and output a signal compatible with the Media Independent Interface (MII) bus specifications. The input signal may comprise from one to four pairs depending on the configuration with each pair comprising a 25 Mbps signal. The BCM5203 100Base-Tx Quad Transceiver manufactured by Broadcom Corporation, Irvine, California is suitable for use with the present invention in implementing the 100BaseTX PHY module 184.

The MII signal output from the 100Base Tx module 184 is input to a 2 port MII bridge 186. The bridge 186 functions to couple the MII signals from the module to and from a message memory unit 187 and an MII interface 188. The GT48006 2-Port 10/100 Mbps Ethernet Bridge/Switch Controller manufactured by Galileo Technology, San Jose, California may be used to implement the MII bridge 186. The message memory 187 functions to soak up any differences in data rate between the two sides of the bridge.

Data from the MII bridge 186 is input to the MII interface 188. The MII interface 188 is adapted to receive an MII data stream and output a decoded representation of the data that is stored in the flow and rate control memory 189. The function of the flow and rate control memory 189 is to soak differences in transmitting rates between the 100BaseTX port and the 100BaseS port. The rate difference may be as high as 25 Mbps versus 100 Mbps depending on the number of pairs in use at the 100BaseT and 100BaseS ports. The controller is adapted to manage, administer and control the MII interface and the data splitter 190.

The data splitter 190 functions to divide the single data stream previously stored in the flow and rate control memory 189 into from one to four separate output data streams. The invention employs the technique of inverse multiplexing, i.e., spreading a single high data rate signal over several lower data rate channels, to achieve a high data rate at the 100BaseS output. Each output data stream is destined to a separate DSL Ethernet port 196 via data lines

202 that are input to the DSL Ethernet Ports #1 through #4. Four DSL Ethernet ports 196 are shown, labeled DSL Ethernet Port #1 through #4. From one to up to four DSL Ethernet Port modules can be used depending on the 100BaseS configuration actually implemented. The invention supports up to four DSL Ethernet Ports for a data range from 25 to 100 Mbps in 25 Mbps increments.

Each DSL Ethernet Port 196 comprises a modem module that functions to modulate the data stream input from the data splitter 190 to a 100BaseS signal 198. The modem module also functions to demodulate the received 100BaseS signal to an output data stream that is input to the data collection and reorganization unit 192. The unit 192 functions to receive the demodulated data from up to four DSL Ethernet Port modules via control/data lines 204 and assemble the one or more data streams into a single data stream and store it in the flow and rate control memory 189. The data is then read from the memory 189 and input to the MII interface 188. The MII interface outputs the data in MII format to the 100BaseT PHY module 184 via the MII bridge 186. The 100BaseT PHY module converts the data from MII format into a 100BaseT Ethernet compatible signal 182.

The modem has the capability to automatically sense the number of DSL Ethernet Port cards 196 installed in the system. A configuration and auto sense unit 200 provides this functionality via one or more control/data lines 206 to and from the port modules 196. The determination of the number of port cards 196 installed is received by the controller 194 via control lines 208. The controller, in turn, configures and controls the MII interface, data splitter 190, data collection and reorganization 192 and configuration and auto sense units accordingly.

The output of each DSL Ethernet Port module 196 is a 25 Mbps data stream (payload rate). The data output of the modem comprises the upstream channel. The 25 Mbps raw data rate is used to generate a 28.125 Mbps linear rate data stream which includes protocol overhead such as forward error correction coding, headers, control information, etc. The upstream channel is transmitted using QAM 16 wherein each symbol represents 4 bits. The baud rate for the upstream channel is given by

$$\begin{aligned}\text{upstream baud rate} &= \frac{28.125 \text{ Mbps}}{4 \text{ bits/symb}} \\ &= 7.0313 \text{ Msymbols/s}\end{aligned}\tag{1}$$

The bandwidth required, using 20% excess, for the upstream channel is thus  $1.2 \times 7.0313 = 8.4375$  MHz. Using a sampling rate twice that of the data rate  $2 \times 28.125 = 56.25$



Msamples/sec yields a ratio of the sampling rate to baud rate equal to 8. A suitable analog to digital converter (ADC) for use with the present invention to sample the received 100BaseS signal is the AD6640 12-bit ADC featuring a sampling rate of 65 Msamples/sec, available from Analog Devices, Norwood, Massachusetts.

5           The downstream channel also utilizes QAM for its modulation but rather than QAM 16, the downstream channel utilizes QAM 64. In this case, each symbol represents 6 bits and the baud rate for the downstream channel is given by

$$\begin{aligned}\text{upstream baud rate} &= \frac{28.125 \text{ Mbps}}{6 \text{ bits/symb}} \\ &= 4.6875 \text{ Msymbols/s}\end{aligned}\tag{2}$$

10           The bandwidth required, using 20% excess, for the downstream channel is thus  $1.2 \times 4.6875 = 5.6250$  MHz. Using a sampling rate twice that of the data rate, i.e., 56.25 Msamples/sec, yields a ratio of the sampling rate to baud rate equal to 12.

15           The spectrum diagram of the 100BaseS signal comprising both upstream and downstream signals is shown in Figure 5. The channel comprises a 5.625 MHz downstream portion 210 that spans frequencies from approximately 0.3125 MHz to 5.9375 MHz with a center frequency  $f_c$  of 3.125 MHz. The channel also comprises an 8.4375 MHz upstream portion 214 that spans frequencies from approximately 7.0313 MHz to 15.4688 MHz with a center frequency  $f_c$  of 11.25 MHz. Residing in between the downstream and upstream portions is a guard band spacing of approximately 15% of the center frequency.

#### Modem Transmitter

20 <sup>JSAS7</sup> A block diagram illustrating the transmit portion of the 100BaseS modem of the present invention in more detail is shown in Figure 6. Note that each DSL Ethernet Port cards 196 (Figure 4) comprises an independent modem transmitter and receiver. Therefore, the following description of the modem transmitter and receiver applies to each DSL Ethernet Port card. The data source feeding the modem supplies a transmit data signal and a transmit enable signal to the transmitter interface 80 of the 100BaseS modem. The transmit interface inputs digital data to the frame first in first out (FIFO) 82. The FIFO functions to adjust the rate of data flow between data source and the modem itself. The FIFO compensates for differences in the data rates between the two devices. The output of the FIFO is input to a sync generator 91, header generator 89 and the randomizer 84. The sync generator functions to generate and output two sync bytes to the frame formatter 89. Preferably, the two sync

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output. The center frequency and the bandwidth of the notch filter is set to cover the amateur radio band.

The output of the mux 36 is input to an in phase filter 38, a quadrature filter 40 and a timing control circuitry 48. The I and Q signals, output of the in phase and quadrature filters, respectively, are input to the adaptive equalizer 42. The I and Q outputs of the adaptive equalizer are input to the slicer 44. The slicer generates a feedback signal to control the adaptive equalizer and the timing control circuitry. The timing control circuitry outputs a signal to the voltage controlled crystal oscillator (VCXO)/phase lock loop (PLL) 50. The output of the PLL is input to clock generating circuitry that functions to produce the clock signals used internally by the modem.

The I and Q outputs of the slicer are input to the symbol decoder 46 which functions to make a best determination from among the constellation points according to the I and Q input signals. The bits representing the symbol are output by the symbol decoder and input to the frame deformatter 53. The frame deformatter is coupled to the deinterleaver 54, decoder 66 and the sync detector 68. The sync detector functions to match the sync pattern and hunt for multiple sync occurrences in the input data stream. Once a sync is detected, the header data is read from the frame by the frame deformatter and input to the decoder 66. The output of the decoder is input to the derandomizer 70. The output of the decoder and the derandomizer are input to the header analyzer 64. The header is analyzed to detect missing frames, perform addressing functions, etc.

The frame deformatter also outputs a data stream to the deinterleaver 54 that functions to deshuffle the data. The output of the deinterleaver is input to the decoder 56. The output of the decoder is input to the derandomizer 58 which functions to descramble the data. The output of the derandomizer is input to the frame FIFO 60 which adjusts for the difference in data rates between the modem and the communication device connected to it. The output of the frame FIFO is input to the receive interface 62 which outputs a receive data signal. A receive clock generated by the data device connected to the modem is input to the receive interface and functions to provide the clocking signal for the receive data.

### Modulation Characteristics

The modulation characteristics of the 100BaseS system of the present invention will now be described in more detail. The 100BaseS system can transmit at full duplex on one to four category 3 or 5 (CAT-3 or CAT-5) shielded or unshielded twisted pair (UTP) wires,

utilizing frequency division multiplexing (FDM). The system supports a rate transmission of 28.125 Mbps in each direction simultaneously. The payload rate, after accounting for forward error correction (FEC), control overhead, control information, etc. is 25 Mbps on each twisted pair wire. Thus, the system supports payload transmission rates of 25, 50, 75 and 100 Mbps.

The system utilizes quadrature amplitude modulation (QAM), with a square root raised cosine shaping filter at the transmitter and a matched filter at the receiver. The roll-off factor of the square root raised cosine filter is 0.2. The downstream channel utilizes QAM-64, providing a spectral efficiency of 6 bits/symbol. The upstream channel utilizes QAM-16, providing a spectral efficiency of 4 bits/symbol.

The upstream channel uses QAM-16 with less bits per symbol than the modulation used for the downstream channel due to the attenuation of the telephone line at higher frequencies. The upstream channel band is placed at a higher frequency than the downstream channel. Thus, the bandwidth of the upstream channel is necessarily higher in order to achieve the same data rate.

The transmitted power output by the system onto the twisted pair wire is preferably limited to 10 dBm (10 mW) in each direction. This power limit is widely incorporated into existing standards such as ANSI and ETSI. The transmit power is limited in order to limit the power spectral density (PSD) on the wire. The downstream power is thus fixed but the power transmitted on the upstream direction is controlled by the downstream link in accordance with the length of the wire so as to maintain the received power in the upstream direction at a constant level. Transmit power control is necessary in order to prevent excessive far end crosstalk to other upstream channels.

The performance of the system is affected by several noise sources. One of these noise sources is far-end cross talk (FEXT). The power spectral density (PSD) introduced by the FEXT can be described by Equation 3 below.

$$PSD_{FEXT}(f) = PSD_{Tx} \cdot |H(f)| \cdot \left(\frac{N}{49}\right)^{0.6} (9 \times 10^{-20}) \cdot d \cdot f^2 \quad (3)$$

where  $PSD_{Tx}$  is the power spectral density of the transmitted signal,  $N$  is the number of disturbers, i.e., the number of wire pairs used to transmit the 100BaseS signal (from 1 to 4),  $d$  is the distance of the wire in feet and  $f$  is the frequency of radiation in Hz. The PSD,  $S_R(f)$ , of the received signal can be expressed as the following

$$S_R(f) = S_T(f) \cdot |H(f)|^2 \quad (4)$$

where  $S_T(f)$  is the PSD of the transmitted signal and  $H(f)$  is the frequency response or the transfer function of the twisted pair at the specified wire length.

A diagram illustrating the far end cross talk at 500 meters for a sample implementation of the 100BaseS is shown in Figure 8. Two curves are shown in the graph, one for a single twisted pair ( $N=1$ ) and for three twisted pairs ( $N=3$ ). Using the curve for three twisted pairs as an example, the FEXT for the upstream channel is approximately -22 dB which is acceptable since QAM 16 requires 19 dB. Likewise, the FEXT for the downstream channel is approximately -30 dB which is also acceptable, as QAM 64 requires 25 dB.

Another type of noise is near-end crosstalk (NEXT). The system, however, does not generate near end cross talk because there is no overlap in frequency between the upstream frequency band and the downstream frequency bands in the same binder.

Yet another source of noise that can affect system performance is thermal noise. Typical thermal noise  $N_0$  in the system is at a one sided power level of -140 dBm/Hz. Thermal noise, however, can be neglected when compared to the effect of self FEXT from the other zero to three lines.

After FEC, the bit error rate (BER) is  $10^{-9}$  or less. As described below, the performance specified above is achieved with a 6 dB margin. The maximum ranges listed in the table above are supported by the mathematical calculations presented below.

The capacity and range of the system will now be described in more detail. The theoretical upper limit on the number of bits per second, i.e., capacity, of a transmission channel is given by the well know Shannon formula

$$C = \int_{f_{\min}}^{f_{\max}} \log_2 \left[ 1 + \frac{S_R(f)}{N(f)} \right] df$$

where  $f_{\min}$  and  $f_{\max}$  are the lower and upper frequencies of the channel,  $S_R(f)$  is the power spectral density of the received signal and  $N(f)$  is the power spectral density of the noise. The power spectral density of the noise is given by

$$N(f) = N_{FEXT}(f) + N_0 \quad (5)$$

The power spectral density of the received signal is as given above

$$S_R(f) = S_T(f) \cdot |H(f)|^2 \quad (6)$$

where  $S_T(f)$  is the power spectral density of the transmitted signal. The transmitted signal is a raised cosine with a bandwidth excess of 20% and total power of 10 dBm.  $H(f)$  is the frequency response or the transfer function of the twisted pair at the specified wire length. Since it is preferable to have a 6 dB margin in system performance, the Shannon capacity formula is utilized with an artificial factor of 0.25, i.e.,  $0.25 \cdot S(f)$  is used rather than  $S(f)$ .

The full channel capacity cannot be achieved with QAM modulation, but trellis coding can be used to get close to the full capacity. Without trellis coding, QAM modulation can achieve 50% or more of the capacity using sufficiently rich constellations. As a rule of thumb, QAM modulation with  $L$  constellation points can be used to transmit approximately  $\log_2 L$  bits/symbol at a BER of  $10^{-5}$ , before forward error correction, if the following expression is satisfied for the signal to noise ratio (SNR)

$$SNR \geq 6 + 3 \log_2 L \text{ dB} \quad (7)$$

The SNR can be defined as

$$SNR = \frac{1}{f_{\max} - f_{\min}} \frac{\int_{f_{\min}}^{f_{\max}} S_R(f) df}{\int_{f_{\min}}^{f_{\max}} N(f) df} \quad (8)$$

In the system of the present invention QAM-256 can be utilized if the SNR of the channel is at least 30 dB. QAM-16 can be utilized if the SNR of the channel is at least 18 dB. However, a 6 dB noise margin is preferably added to these numbers to yield a threshold of 36 dB for QAM-256 and a threshold of 24 dB for QAM-16.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.